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ALTITUDE DEPENDENCE OF THE ELECTROMAGNETIC SPECTRA INITIATED BY PRIMARY NUCLEON AIR COLLISIONS

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A study has been made of the altitude dependence of high-energy spectra of electromagnetic components initiated by primary cosmic nucleon – air collisions. The primary cosmic nucleon spectrum has been estimated from the directly measured elemental fluxes at high energies obtained from the recent absolute measurements by different groups. Considering the superposition model, the estimated all-particle primary nucleon spectrum follows approximately the form $2.56E^{-2.73}$ in the energy range 0.1 - 100 TeV. Taking this as the source of parent neutral mesons and the spectrum-weighted moments for neutral pion production after Aguilar Benitez et al., the neutral pion production spectrum in the atmosphere has been calculated. The generated neutral pions decay before reacting in the atmosphere. Therefore, the electromagnetic cascades are generated through $\pi^0 \rightarrow 2\gamma$ decays. The unidirectional intensity of γ-rays at atmospheric depths of 540 and 735 $\mathrm{g\,cm^{-2}}$ air have been calculated by adopting the conventional cascade theory, discussed earlier by Bhattacharyya and Roychoudhury. The results are found comparable to the emulsion chamber data obtained at locations Mt. Chacaltaya and Mt. Norikura. We also estimated the spectra of gamma rays and electrons at Mt. Kanbala and Mt. Fuji at atmospheric depths 520 and 650 $\mathrm{g\,cm^{-2}}$, with the adopted value of mean free path of electromagnetic component in air as $\Lambda_{em} \simeq 120\ \mathrm{g\,cm^{-2}}$ from Daniel and Stephens. It is found that our result is in accord with the experimental data obtained by Ren et al. at Mt. Kanbala while it is in approximate agreement with the observed data of Shibata et al. at Mt. Fuji.

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1. *Introduction*

In gamma-ray astronomy, the evolution of primary cosmic rays in the Galaxy is observed and studied. In general, secondary gamma rays are produced by inelastic interactions of primary particles with the gas in the interstellar medium.

The search for gamma-ray bursts is of astrophysical importance for the study of emission of neutrinos from the sources of gamma rays. Halzen and Jaczko [1] have recently considered ultrarelativistic fire-balls and cosmic strings to interpret the experimental results. Gamma rays and neutrinos are produced in beam dumps during the interaction of high-energy protons with stellar targets. In such reactions, gamma rays and neutrinos are generated simultaneously through the decay of neutral and charged pions, respectively. The discovery of cosmic microwave background also reveals the fact that Universe would not be transparent to gamma rays above 100 TeV due to the photon-photon interactions. Underground muon detectors are designed so that they can measure the direction of arrival of downgoing muons originating from gamma-ray–induced electromagnetic showers in the earth's atmosphere. In general, gamma-ray showers are muon poor, so long observations of muon events are required in GeV or TeV muon telescopes to determine the direction of incident gamma rays from astronomical sources. Investigation of gamma ray bursts also provides the data on dark matter and requires a km-size muon telescopes for the identification of the sources. This helps the search of dark matter in active galactic nuclei. The study of diffuse gamma rays generated by the primary cosmic-ray interactions with the atmosphere is of sufficient importance to estimate the background gamma-ray fluxes and to isolate the radiation reaching the earth from different astronomical objects like Crab Nebula, Cygnus X-3, pulsars and AGN [2-5].

Usually the charged pions are produced in the upper atmosphere by primary nucleus-nucleus collisions and they decay into muons and neutrinos, except at very high energies when the time dilation of the relativistic mesons dominates. A portion of low-energy muons decay to electrons and neutrinos. On the other hand, the produced neutral pions decay into gamma rays that penetrate the atmosphere producing cascade showers consisting of electrons and photons. Earlier Daniel and Stephens [6] have surveyed the spectra of electrons and gamma rays produced by neutral pions in the upper atmosphere at moderate energies of less than 0.1 TeV. Okuda and Yamamoto [7] have studied electron-photon spectra using analytic cascade theory for energies above 1 GeV. Later, Beuermann and Wibberenz [8] have extended such calculations to the energy range 4 MeV to 10 GeV. Daniel and Stephens [9] have also determined similar spectra from near the top of the atmosphere up to the sea level. Jabs and Wibberenz [10] have calculated the energy spectrum of secondary gamma rays at atmospheric depths 0 – 30 g cm^{-2} in the spectral range 1 to 13 GeV.

Earlier, Lattes et al. [11] and Otwinowski [12] investigated the energy spectra of diffuse photons at atmospheric depths 540 and 735 $\text{g}\,\text{cm}^{-2}$ in the spectral energy range 0.2 – 10 TeV. Recently, Saito et al. [13] have studied the high-energy air showers using Monte Carlo simulations and have compared their results with the observed data obtained at Mt. Norikura. They have used the primary spectrum in the energy range $10^3 - 10^4$ TeV. From a closer survey of JACEE and others [14-22] on primary spectrum and Fuji Kanbala experimental data (Ren et al. [23]), it may be concluded that the proton energy spectrum shows a bending behaviour beyond 1000 TeV. So, it is expected that the secondary photon energy spectra at different atmospheric depths may have a steepening in the energy range beyond 100 TeV. Investigations of the proton energy spectrum in the knee region is necessary for the understanding of the the acceleration mechanism and propagation of high-energy primary cosmic rays in the Galaxy. The large-scale emulsion-chamber experiment at high mountain altitude performed by Ren et al. [23] has exhibited a peculiar structure of electron-photon air shower sizes.

The availability of the balloon and satellite-borne passive and active detector experiments have allowed us to estimate precise primary nuclear spectra up to energies $\leq$1000 TeV. This may be utilized to study sources of parent particles generating electron-photon components in the TeV energy range. With the adoption of the conventional cascade equation [24–26], the photon spectra at different atmospheric depths of 540 and 735 $\mathrm{g\,cm^{-2}}$ have been estimated. The derived results have been compared with the available results at different mountain altitudes [11,12].

Using a similar electromagnetic-cascade equation, the photon flux and the electron component at depths 520 and 650 $\mathrm{g\,cm^{-2}}$ has been derived using the simplified cascade formulation of Gaisser [27]. In such calculations, the electromagnetic attenuation length related to the radiation length of electromagnetic cascade theory has been obtained from the survey of Daniel and Stephens [6]. The results have been compared with the experimental data of Ren et al. [23] and Shibata et al. [28] performed at Mt. Kanbala in Tibet at an altitude of 5500 m and at Mt. Fuji, respectively.

2. *Nuclear physics*

The differential primary cosmic-ray elemental spectra for the i-th species follow the power law

$$N_i(E)\mathrm{d}E = K_i E^{-(\gamma_i+1)}\mathrm{d}E\,, \tag{1}$$

where K_i, γ_i and E are the elemental spectral amplitudes, indices of the i-th species and energy per nucleon, respectively.

By adopting the standard superposition model [29,30], one can obtain the total primary-nucleon spectrum as

$$N(E)\mathrm{d}E = \sum_{i=\mathrm{H}}^{\mathrm{Fe}} N_i(E)\mathrm{d}E = \sum_{i=\mathrm{H}}^{\mathrm{Fe}} A_i K_i E^{-(\gamma_i+1)}\mathrm{d}E \simeq K E^{-(s+1)}\mathrm{d}E\,, \tag{2}$$

where K and s are the spectral amplitude and integral spectral index of the total primary-nucleon energy spectrum incident on the top of atmosphere, respectively.

The CERN accelerator data on p_T integrated Lorentz-invariant cross-section for the p + p → π^0+ X inclusive reaction found by Aguilar-Benitez et al. [31] follows the relation

$$x\frac{\mathrm{d}\sigma}{\mathrm{d}x} = A(1-x)^n\,, \tag{3}$$

where A and n are fitting parameters.

The spectrum-weighted moments for the p + p → π^0+ X inclusive collisions can be estimated from the relation

$$Z_{p\pi^0} = \int\limits_0^1 x^{s-1} f_{p\pi^0}(x)\mathrm{d}x \tag{4}$$

where

$$f_{p\pi^0}(x) = \frac{\pi}{\sigma_{in}}\int\limits_0^\infty E\left(\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p}\right)\mathrm{d}p_T^2 = A(1-x)^n\,,$$

The simplified form of the Z-factor follows

$$Z_{p\pi^0} = \frac{A\Gamma(s)\Gamma(n+1)}{\sigma_{in}\Gamma(s+n+1)} \qquad (5)\,.$$

The neutral meson production spectrum $g_{\pi^0}(E)$dE can be estimated from the primary nucleon spectrum and their inelastic interactions with the atmospheric nuclei near the top of the atmosphere using the relation

$$g_{\pi^0}(E)\mathrm{d}E = Z_{p\pi^0}N(E)\mathrm{d}E \qquad (6)\,.$$

The lifetime of neutral pion is short and they decay into two photons through the $\pi^0 \to 2\gamma$ process. The energy spectrum of photons $g_\gamma(E)$ may be estimated from the neutral pion production spectrum $g_{\pi^0}(E)$ using the relation

$$g_\gamma(E)\mathrm{d}E = \frac{2}{s+1} g_{\pi^0}(E)\mathrm{d}E \tag{7}$$

The unidirectional flux of gamma rays at an atmospheric depth X (g cm^{-2}), produced by the incident parent gamma rays, can be estimated using the following expression [24-26]

$$g_\gamma(E,X) = g_\gamma(E)\left[\frac{K_1(s)\{\exp(\lambda_1(s)X/\lambda_0) - \exp(-X/L)\}}{1+\lambda_1(s)L/\lambda_0} + \frac{K_2(s)\{\exp(\lambda_2(s)X/\lambda_0) - \exp(-X/L)\}}{1+\lambda_2(s)L/\lambda_0}\right] \tag{8}$$

where s is the integral primary nucleon spectral index, L is the absorption length of p-air collisions and λ_0 the photon radiation length. Here

$$K_1(s) = \frac{a_1 C(s)}{\sigma_0 + \lambda_1(s)}, \qquad \text{and} \qquad K_2(s) = \frac{a_2 C(s)}{\sigma_0 + \lambda_2(s)}\,.$$

$\sigma_0, \lambda_1(s)$ and $\lambda_2(s)$ are conventional parameters in the cascade theory [24] and they obey the respective forms

$$A(s) = 1.36\frac{\mathrm{d}}{\mathrm{ds}}\ln(s+1)! - \frac{1}{(s+1)(s+2)} - 0.0750,$$

$$B(s) = 2\left[\frac{1}{(s+1)} - \frac{1.36}{(s+2)(s+3)}\right],$$

$$C(s) = \left(\frac{4}{3} + 2b\right)\left(\frac{1}{s} - \frac{1}{s+1} + \frac{1}{s+2}\right),$$

$$\lambda_1(s) = -\frac{A(s)+\mu_0}{2} + \frac{1}{2}\sqrt{[A(s)-\mu_0]^2 + 4B(s)C(s)},$$

$$\lambda_2(s) = -\frac{A(s)+\mu_0}{2} - \frac{1}{2}\sqrt{[A(s)-\mu_0]^2 + 4B(s)C(s)}\,.$$

Gaisser [27] has given a simplified procedure for the derivation of the photon flux together with electromagnetic components at an atmospheric depth X using the conventional electromagnetic cascade equation. The analytic function scale and the solution follows the power law within the boundary condition

$$\frac{\mathrm{d}N_{\gamma+e^{\pm}}(E)}{\mathrm{d}E} = CK_\gamma E^{-(s+1)} e^{-X/\Lambda_{em}} \tag{9}$$

where $g_\gamma(E)\mathrm{d}E \simeq K_\gamma E^{-(s+1)}\mathrm{d}E$ is the photon flux incident on the top of the atmosphere, i.e., just before entering the atmosphere, where the corresponding atmospheric depth is $X = 0$; Λ_{em} is the electromagnetic depth attenuation length; C is a constant approximately given by $1 + N_{e^{\pm}}/N_\gamma$, a function of integral spectral index of photons.

3. *Results and discussion*

The elemental primary spectra of H, He, CNO, Ne-Si and Fe nuclei obtained from active and passive detector experiments by JACEE (Asakimori et al. [17]), IMAX (Menn et al. [22]), Webber et al. [15], SOKOL (Ivanenko et al. [19]), CRN (Muller et al. [18]), Ryan et al. [14], Kawamura et al. [16], Dwyer et al. [20] and

Buckley et al. [21] are shown in Figs. 1 and 2, fitted by the power law (1) whose spectral amplitudes K_i and indices γ_i are shown in the Table 1.

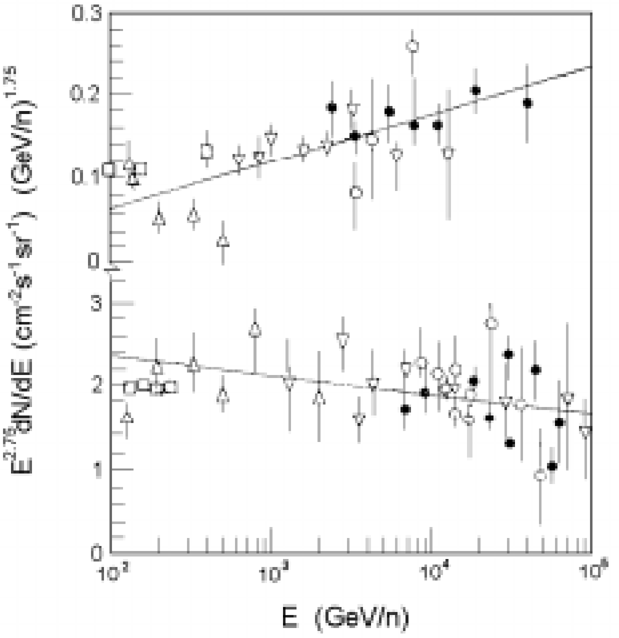

Fig. 1. Energy spectrum of He *nuclei (upper set of data) obtained from direct measurements using ballons and sattelites, △ Ryan et al. [14], ○ Kawamura et al. [16], • JACEE [17], ▽ SOKOL [19], □ Dwyer et al [20]. Full curve is the power law fit to the* He *flux whose spectral amplitude and index are shown in the Table 1. Energy spectrum of protons (lower set of data) obtained from the direct measurements using balloons and satellites, △ Ryan et al. [14], ○ Kawamura et al. [16], • JACEE [17], ▽ SOKOL [19], □ IMAX [22]. Full curve is the power law fit to the proton flux whose spectral amplitude and index are shown in the Table 1.*

TABLE 1. Calculated values of the spectral amplitudes K_i [cm^2 s sr GeV]$^{-1}$ *and indices γ_i obtained from the power law fit (1) to the elemental fluxes measured by different groups [14-22].*

Element	A_i	K_i	γ_i
H	1	2.979×10^{-0}	1.80
He	4	3.765×10^{-2}	1.59
CNO	14	42.530×10^{-3}	1.57
Ne-Si	28	8.023×10^{-4}	1.57
Fe	56	1.431×10^{-4}	1.54

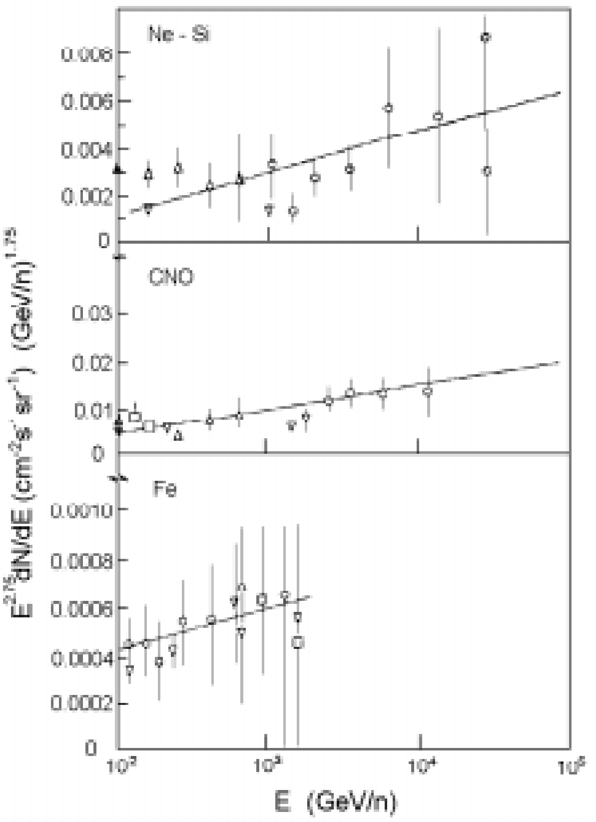

Fig. 2. Energy spectrum of primary cosmic-ray Ne-Si *nuclear fluxes (upper data) obtained from direct measurements using balloon and sattelites, △ Ryan et al. [14], ○ JACEE [17], ▽ SOKOL [19]. The full curve is the fit to the* Ne-Si *flux and the corresponding amplitude and spectral index are given in Table 1. Energy spectrum of primary cosmic-ray* CNO *nuclear fluxes (data in the middle) obtained from direct measurements using balloon and satellites, △ Ryan et al. [14], ○ JACEE [17], ▽ SOKOL [19], □ Buckley et al. [21]. Full curve is the power law fit to the* CNO *flux whose spectral amplitude and index are shown in the Table 1. Energy spectrum of primary cosmic ray* Fe *nuclear flux (lower data) obtained from directly measured balloon and satellite experiments, ○ Kawamura [16], □ JACEE [17], ▽ SOKOL [19]. Full curve is the fit to* Fe *nuclei flux data whose parametric values are displayed in Table 1.*

Using the relation (2), the total primary nucleon spectrum at the top of the atmosphere has been estimated and found to follow the form

$$N(E)\mathrm{d}E = 2.56\,E^{-2.73}\ \mathrm{d}E\ [\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV}]^{-1} \qquad (10)$$

where E is the nucleon energy expressed in GeV units and the relation holds well for the energy range $10^2 - 10^5$ GeV.

In connection with the derivation of π^0 production spectrum in the atmosphere, the Lorentz invariant cross-section for inclusive reactions p + p $\rightarrow$ π^0+ X has been considered from the results of CERN LEBC-EHS experiments performed by Aguilar-Benitez et al. [31]. Figure 3 presents their π^0 production $\mathrm{d}\sigma/\mathrm{d}x_F$ data along with the numerical fit to the data available from the fit (3) for $A = 15.39$ mb and $n = 3.97$.

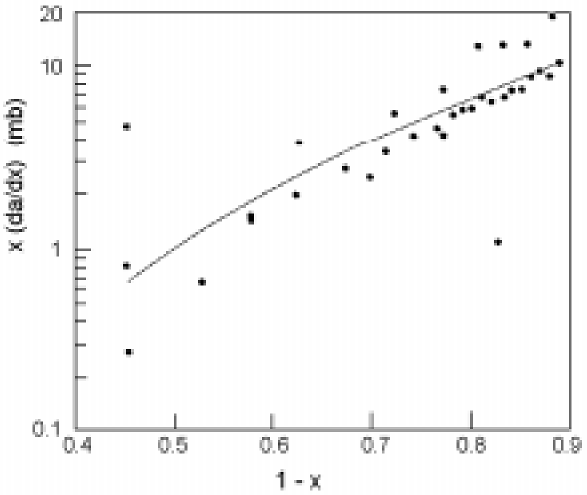

Fig. 3. Neutral-pion-production inclusive cross-section $\mathrm{d}\sigma/\mathrm{d}x_F$ *data obtained from the CERN LEBC-EHS experiments, • Aguilar-Benitez et al. [31]. Full line is the numerical fit to the data as obtained from the relation (3).*

Using the relation (5), the spectrum-weighted moment for neutral pion production, $Z_{p\pi^0}$, has been calculated for $\sigma_{in} = 35$ mb, and $s = 1.73$ and found to be 0.022315. The primary-nucleon-initiated neutral-pion production spectrum and the corresponding photon spectrum in the atmosphere have been calculated from Eqs. (5) to (7) and found to follow the relations

$$g_{\pi^0}(E)\mathrm{d}E = 0.057\,E^{-2.73}\ \mathrm{d}E \quad [\mathrm{cm}^2\mathrm{s\,sr\,GeV}]^{-1}\,, \tag{11}$$

and

$$g_{\gamma}(E)\mathrm{d}E = 0.042\,E^{-2.73}\ \mathrm{d}E \quad [\mathrm{cm}^2\mathrm{s\,sr\,GeV}]^{-1}\,. \tag{12}$$

By adopting the standard parameters, like absorption length of p-air collision, $L = 115\ \mathrm{g\,cm}^{-2}$, radiation length of photons in air, $\lambda_0 = 38\ \mathrm{g\,cm}^{-2}$, and using relations (7) and (8) along with the conventional cascade parameters from Tables 1 and 2, the integral energy spectra of photons at large atmospheric depths $X = 540$

and 735 $\mathrm{g\,cm^{-2}}$ have been estimated and found to follow the power law fits of the forms:

$$g_\gamma(\geq E, 540\ \mathrm{g\,cm^{-2}}) = 4.66 \times 10^{-4}\ E^{-1.73}\quad [\mathrm{m^2\,s\,sr}]^{-1}\,, \tag{13}$$

$$g_\gamma(\geq E, 735\ \mathrm{g\,cm^{-2}}) = 1.063 \times 10^{-4}\ E^{-1.73}\quad [\mathrm{m^2\,s\,sr}]^{-1}\,. \tag{14}$$

The cascade parametric values obtained from relations discussed in the text after Rossi [24] have been displayed in Table 2.

TABLE 2. The cascade parametric values after Rossi [24].

$A(s)$	$B(s)$	$C(s)$	μ_0	K_1	K_2	λ_1	λ_2
1.1870	0.5804	0.5595	0.7730	0.5783	0.2839	-0.3737	-1.5863

The derived integral energy spectra of photons at the atmospheric depths 540 $\mathrm{g\,cm^{-2}}$ and 735 $\mathrm{g\,cm^{-2}}$ have been displayed in Fig. 4 along with the high-altitude emulsion-chamber data of Lattes et al. [11] and Otwinowski [12], at locations Mt. Chacaltaya and Mt. Norikura, respectively. An approximate agreement of the de-

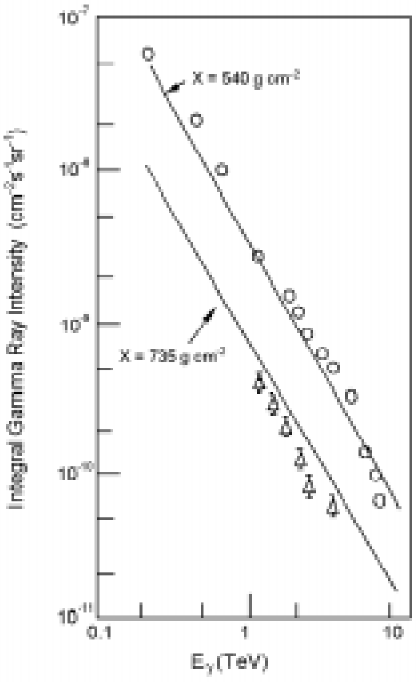

Fig. 4. Energy spectra of secondary diffuse photons generated by primary nucleon–air inelastic interactions: experimental emulsion chamber data, ○ Lattes et al. [11] at location Mt. Chacaltaya ($X = 540\ \mathrm{g\,cm^{-2}}$) and △ Otwinowski [12] at location Mt. Norikura ($X = 735\ \mathrm{g\,cm^{-2}}$). Solid lines are the derived photon energy spectra at two atmospheric depths $X = 540$, and 735 $\mathrm{g\,cm^{-2}}$, respectively.

rived photon energy spectra below 10 TeV from the primary nucleon spectrum reveals the fact that the conventional cascade formulation and Feynman scaling phenomena are still in favourable position for the altitude variation of the secondary electromagnetic components of primary cosmic rays. We could not extend our calculations beyond 10 TeV photon energy due to the non-availability of data as well as statistical uncertainty of the available results. The scale-breaking phenomena in H-H collisions may interprete the spectral bending phenomena, i.e. the knee region of the primary cosmic ray spectrum [13].

Considering the simplified cascade formulation (6) after Gaisser [27] and adopting the initial photon spectrum at the top of the atmosphere ($X = 0$) from the relation (9), the photon and electron components generated at atmospheric depths $X = 520$ and 650 $\mathrm{g\,cm^{-2}}$, at locations Mt. Kanbala and Mt. Fuji, have been estimated and the results are compared with the experimental results of Ren et al. [23]

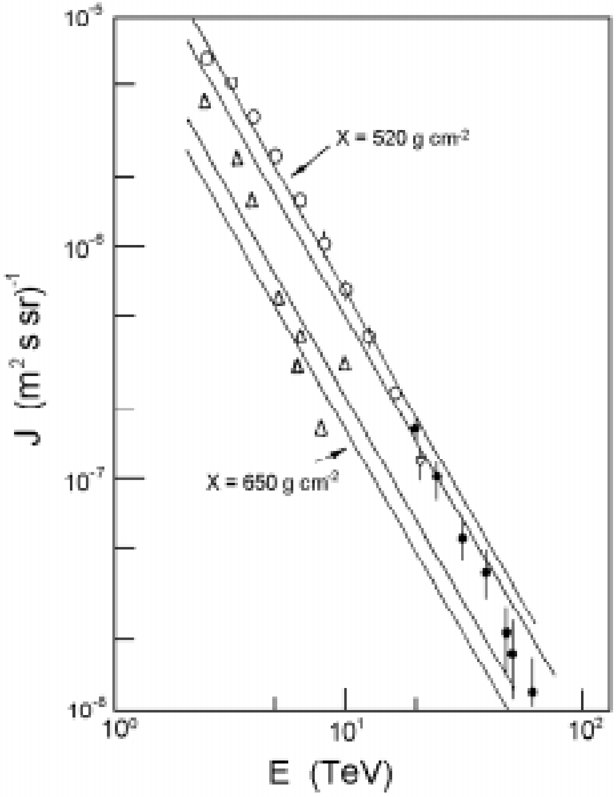

Fig. 5. Integral energy spectrum of $\gamma + e^{\pm}$ on Mt, Kanbala at an altitude of 5500 m *in Tibet: Experimental data,* • *and* ○ *Ren et al. [23] obtained from lead and iron emulsion chambers, respectively,* △ *Shibata et al. [28] at location Mt. Fuji (X = 650* $\mathrm{g\,cm^{-2}}$*). Hatched area and dotted area represent the present derived results at atmospheric depths 520 and 650* $\mathrm{g\,cm^{-2}}$*, respectively.*

and Shibata et al.[28]. In the derivation, we have adopted $C = 1.18$, and $\Lambda_{em} = 120$ g cm^{-2}. The derived spectra measured on Mt. Kanbala at a depth $X = 520$ g cm^{-2} and on Mt. Fuji at depth 650 g cm^{-2} have been found to follow the forms

$$N_{\gamma+e^{\pm}}(E)\mathrm{d}E = 5.11\ E^{-1.73}\ \mathrm{d}E \quad [\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV}]^{-1}\,, \tag{15}$$

and

$$N_{\gamma+e^{\pm}}(E)\mathrm{d}E = 1.73\ E^{-1.73}\ \mathrm{d}E \quad [\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV}]^{-1}\,. \tag{16}$$

Figure 5 shows the comparison of the derived electron-photon spectrum with the observed results of Ren et al. [23] and Shibata et al. [28]. An uncertainty in the calculation may arise due to the choice of the flux ratio $N_\gamma/N_{e^\pm}$ which is 0.18 for the present case. It shows that our theoretical curve is flatter than the experimental curve obtained by Shibata et al.[28]. We have constructed the primary nuclear spectra using the latest results of active and passive detector experiments [14-23]. The energy spectral index obtained from our investigation is about 1.73 which is smaller than the fitted value obtained from experimental results of Shibata et al. [23].

4. *Conclusion*

Starting from the primary nucleon spectrum based from the latest direct active and passive detector measurements, and by adopting the conventional cascade equation, the photon energy spectra at different atmospheric depths have been derived. The results are in fair agreement with the observed results at Mt. Chacaltaya and Mt. Norikura obtained by Lattes et al. and Otwinowski. The energy spectrum of $\gamma+e^{\pm}$ components have been estimated at different atmospheric depths using the standard formulation after Gaisser where the adopted values of absorption free path of electromagnetic component was taken as 120 g cm^{-2}. The present estimate is in accord with the data at different energies obtained by Ren et al. at Mt. Kanbala (at an atmospheric depth 520 g cm^{-2}). An approximate agreement of our derived result with the data obtained by Shibata et al. at Mt. Fuji has been found.

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VISINSKA OVISNOST ELEKTROMAGNETSKIH SPEKTARA PROIZVEDENIH PRIMARNIM SUDARIMA NUKLEONA SA ZRAKOM

Proučavali smo visinsku ovisnost spektara visokoenergijskih fotona proizvedenih primarnim svemirskim nukleonima u sudarima sa zrakom. Spektar primarnih svemirskih nukleona smo ocijenili preko izravno apsolutno mjerenih elementalnih tokova više grupa. Pomoću modela dodavanja zaključujemo da spektar nukleona svih čestica približno opisuje izraz $2.56E^{-2.73}$ u području energije 0.1 - 100 TeV. Uzevši to zračenje kao izvor neutralnih mezona, uz podatke Aguilar Beniteza i sur. u bazi podataka u CERN-u o relativnim vjerojatnostima tvorbe neutralnih piona, izračunali smo spektar neutralnih piona koje primarni svemirski nukleoni tvore u atmosferi. Proizvedeni se neutralni pioni raspadaju prije interakcije u atmosferi te tvore elektromagnetske kaskade raspadima $\pi^0 \rightarrow 2\gamma$. Izračunali smo jednosmjeran intenzitet na atmosferskim dubinama 540 i 735 $\mathrm{g\,cm^{-2}}$.